LINKÖPING UNIVERSITY
DIVISION OF AUTOMATIC CONTROL
ACTIVITY REPORT
2009

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On February 16, 2009 our group suffered a great loss when our key co-worker Anna Hagenblad passed away. She was just 37 years old and is survived by her husband Jan-Erik Eklund and three young sons, Simon, David and Nils.

Anna finished her M. Sc. in Applied Physics and Electrical Engineering in 1995, and started her Ph. D. studies at the Division of Automatic Control the same year. Her research was about identification of nonlinear systems and she completed the Techn. Lic. degree in 2000. She was working on the final stages of her Ph. D. thesis when she was struck by the disease. Her influential paper on Wiener models appeared in Automatica, just a few months before she passed away.

Anna early showed her talent for teaching and was repeatedly nominated for educational prizes by the students. As our Director of Studies she was instrumental for the National Teaching Excellence Award that the group won in 2008.

Anna had great social gifts and became a natural, popular and much-liked center of the division's social life. The atmosphere in the coffee-room will never be the same without her.

Chapter 1

Introduction

The Division of Automatic Control consists of some forty-five persons. We teach thirteen undergraduate courses to more than a thousand students. The courses cover both traditional control topics and more recent topics in model building and signal processing. As highlights for 2009 the following events could be mentioned:

- Per-Johan Nordlund and Henrik Tidefelt defended their doctoral theses.

- In addition, the following people completed their Techn. Lic. degree: Daniel Ankelhed, Christian Lundquist, Per Skoglar and Christian Lyzell.

- Jeroen Hol was awarded the Best student paper award at the IEEE International Conference on Ultra-Wideband held in Vancouver, Canada, 2009 with the paper Tightly Coupled UWB/IMU Pose Estimation [46].

- In April Thomas B. Schön was awarded Gyllene Moroten 2009. Gyllene Moroten is a prize instituted by LinTek, the student union at the faculty of technology. The prize is given to recognize and reward the best pedagogical achievements during the previous academic year.

- In September the Swedish government announced the support of new strategic research areas. Two of three areas awarded to Linköping have members of the control group as Principal Investigators (PI): *Security Link* with Fredrik Gustafsson as PI and *ELLIIT* (a joint program between Linköping, Lund, Blekinge and Halmstad) with Lennart Ljung as PI.

Research

Our research interests are focused on the following areas:

- *System Identification*: We are interested in a number of aspects ranging from industrial applications to the fundamental theory and properties of algorithms.
- *Non-linear and Hybrid Systems*: Here we are interested both in developing theory for nonlinear systems and to understand and utilize how modern computer algebraic tools can be used for practical analysis and design. Hybrid systems is an important and emerging field covering problems of how to deal with systems with both discrete and continuous phenomena.
- *Sensor Fusion*: Techniques to merge information from several sensors are of increasing importance. We are involved in four different industrial applications of this kind, at the same time as we try to abstract the common underlying ideas. Particle filters play an important role in this context.
- *Robotics Applications*: We have a close cooperation with ABB Robotics, and several projects concern modeling and control of industrial robots.
- *Optimisation for Control and Signal Processing*: Convex optimisation techniques are becoming more and more important for various control and signal processing applications. We study some such applications, in particular in connection with model predictive control.

Details of these research areas are given in the corresponding sections of this report.

Funding

We thank the Swedish Research Council (VR), the Swedish Agency for Innovation Systems (VINNOVA) and the Foundation for Strategic Research (SSF) for funding a major part of our research. The strategic research center MOVIII is funded by SSF. The Linnaeus center CADICS is funded by VR and the Industry Excellence Center LINK-SIC is funded by VINNOVA and industry.

The group is coordinating a major EC project, COFCLUO, regarding clearance of flight control laws. Coordinator is Anders Hansson.

Moreover we have EC funding for participating in the European projects MATRIS and HYCON.

Undergraduate Education

As can be seen in Appendix B, the Division of Automatic Control has extensive education activities with a large number of courses. The teaching staff of the division is also involved in education development and management of the engineering programs within Linköping University.

Svante Gunnarson is responsible for the program area EF (Electronics, Physics and Mathematics) which includes the "Y-program" an award-winning Linköping engineering education program. Inger Klein is the leader of the program area DM (Data and Media), which includes the large D, M and C engineering programs.

Report Outline

In the following pages the main research results obtained during 2009 are summarised. More details about the results can be found in the list of articles and technical reports (See Appendices G and H. Numerals within brackets refer to the items of these appendices). These reports are available free of charge, most easily from our web-site. The next chapter describes how you can search for our publications in our database and download any technical report.

Network Services

Mail addresses

There are a number of ways you can access the work produced at the group. Most convenient is probably to email the person you wish to contact. The email addresses are listed at the end of this activity report. Apart from these shorter but quite arbitrary email addresses you can always use the general form:

Firstname.Lastname@isy.liu.se

e.g., Lennart.Ljung@isy.liu.se. We also have a generic email address:

Automatic.Control@isy.liu.se

or AC@isy.liu.se for short. Emails sent to this address are currently forwarded to our coordinator.

Finally, you can also retrieve reports and software electronically using our World Wide Web services. This is our preferred method of distributing reports.

World Wide Web

The most powerful way to get in touch with the group is probably by using our WWW service. The addresses to our main web page, as well as the web pages for the major centers are:

- http://www.control.isy.liu.se
- http://www.moviii.liu.se
- http://www.cadics.isy.liu.se
- http://www.linksic.isy.liu.se
- http://www.liu.se/pic
- http://er-projects.gf.liu.se/~COFCLUO

When you surf around in our WWW-environment you will find some general information over this group, the staff, seminars, information about undergraduate courses taught by the group and you have the opportunity to download technical reports produced at this group. This is the easiest way to access the group's work, just click and collect.

Our WWW service is always under development. We look forward to your feedback regarding this service. If you have any questions or comments, please send an email to our group of webmasters

rt_www@isy.liu.se

Publications Data Base

Selecting "Publications" in our web pages gives access to our publications database. It allows you to search for publications by author, area, year, and/or publication type. You can also search for words in the title. The result of the search is given either as a click-able list of publications (choose HTML) or a list of BibTEX items (choose Bibtex). Clicking on the publication items brings you to the home page of the publication with further information. Department reports can always be downloaded from the home page, while articles and conference papers refer to a related department report that can be downloaded in .pdf format.

Chapter 2

System Identification

2.1 Introduction

Our research in system identification covers a rather wide spectrum, from general principles to particular applications. Some identification applications are described in Chapter 4 on sensor fusion and some in Chapter 5 on robotics.

2.2 Structure Issues in System Identification

2.2.1 Order and Regressor Selection

A common problem in system identification is to determine which regressors in a linear regression model

$$y(t) = \theta^{\mathrm{T}} f(\varphi(t)) + e(t)$$

that are needed to be able to explain collected data, in some measure, sufficiently well. In some cases, there exists some *a priori* knowledge or preference of which parameters are more important than others to incorporate into the model. For example, one might prefer to use as low number of old output regressors as possible to model the system. Most popular regressor selection methods from the statistical learning community prohibit inducing such structure information into the resulting model. To this end, the regressor selection method of choice in [78] for selecting relevant basis functions in an LPV-ARX system was the *nonnegative garrote* method of L. Breiman. Due to lack of real-life datasets from LPV systems, the method could only be evaluated on simulated data, but the results look promising and an efficient numerical algorithm is provided.

2.2.2 Initialization of Transfer-function Models

A common method for identifying a linear time-invariant transfer-function model from data is the prediction-error method. Since this method usually involves solving a non-convex optimization problem, a good parameter initialization method is important to locate the global optimum. In the last decades, *subspace identification* has developed to become the standard choice of method for estimating state-space models. It is shown in [60] how this method can be extended to estimate transfer-function OE and ARMAX models. The modifications are minor and only involve some intermediate calculations where already available tools can be used. Furthermore, with the proposed method other *a priori* information about the structure can be readily handled, including a certain class of linear gray-box structures. The proposed extension is not restricted to the discrete-time case and can be used to estimate continuous-time models.

2.2.3 Difference Algebraic Methods

Differential algebraic techniques, especially Ritt's algorithm, have shown to be quite useful to analyze the identifiability of certain systems containing only polynomial nonlinearities. The main result in the continuous-time case can be stated as: a model structure is globally identifiable if and only if it can be written as a linear regression model. In particular, this implies that once Ritt's algorithm has been used to rewrite the nonlinear model structure into a linear regression model, the parameter estimation problem becomes trivial. Motivated by the above and the fact that most system identification problems involve sampled data, a version of Ritt's algorithm for the discrete-time case is provided in [61]. This algorithm is closely related to the continuous-time version and enables the handling of noise signals without differentiations.

2.3 Semi-supervised Regression and Manifold Learning

System identification and machine learning are developing mostly as independent subjects, although the underlying problem is the same: to be able to associate "outputs" with "inputs". Particular areas in machine learning of substantial current interest are *manifold learning* and *unsupervised* and *semi-supervised regression.*

Here, we do not seek explicit constructions of the estimate f, but are content by having a scheme that provides an estimate of $f(\varphi^*)$ for any given regressor φ^*. This approach has been termed *Model-on-Demand* or *Just-In-Time* modeling. The term *supervised learning* is also used for such algorithms, since the construction of f is "supervised" by the measured information in y. In contrast to this, *unsupervised learning* only has the information of the regressors $\{\varphi(t), t = 1, \ldots, N_u\}$. In unsupervised classification, the classes are constructed by various clustering techniques. *Manifold learning* deals with unsupervised techniques to construct a manifold in the regressor space that houses the observed regressors.

Semi-supervised algorithms are less common. In semi-supervised algorithms, both labelled and unlabelled regressors,

$$\{(y(t), \varphi(t)), t = 1, \ldots, N_l, \varphi(t), t = N_l + 1, \ldots, N_l + N_u\}$$

are used to construct f. This is particularly interesting if extra effort is required to measure the labels. Thus costly labelled regressors are supported by less costly unlabelled regressors to improve the result.

It is clear that unsupervised and semi-supervised algorithms are of interest only if the regressors have a pattern that is unknown *a priori* .

The main reason that semi-supervised algorithms are not often seen in regression and system identification may be that it is less clear when unlabelled regressors can be of use. Let us consider a pictorial example.

Consider the five regressors shown in the left of Figure 2.1. Four of the regressors are labelled and their labels are written out next to them. One of the regressors is unlabelled. To estimate that label, we could compute the average of the two closest regressors' labels, which would give an estimate of 2.5. Let us now add the information that the regressors and the labels were sampled from an in time continuous process and that the value of the regressor was evolving along the curve shown in the right part of Figure 2.1.

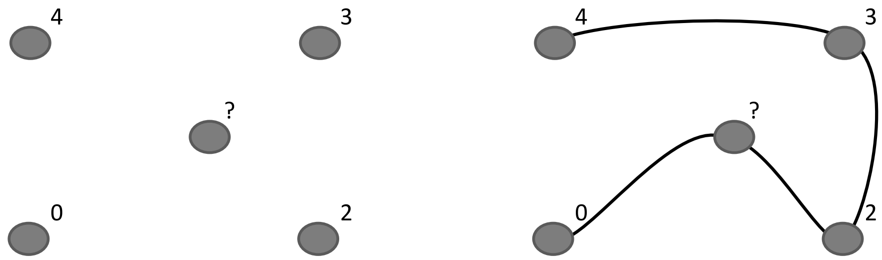


Figure 2.1: The left side shows five regressors, four labelled and one unlabelled. Desiring an estimate of the label of the unlabelled regressor, we could simply weight together the two closest regressors' labels and get 2.5. Say now that the process that generated our regressors traced out the path shown in the right part of the figure. Would we still guess 2.5?

Knowing this, a better estimate of the label would probably be 1. The knowledge of that the regressors are restricted to a certain region in the regressor space can hence make us reconsider our estimation strategy. Notice also that to estimate the region to which the regressors are restricted, both labelled and unlabelled regressors are useful.

Generally, regression problems having regressors constrained to rather limited regions in the regressor space may be suitable for a semi-supervised regression algorithm. It is also important that unlabelled regressors are available and comparably "cheap" to get as opposed to the labelled regressors.

To read more about our work on semi-supervised regression, manifold learning and system identification, see [64, 28, 29, 65].

2.4 Automotive and Aircraft Applications

The current development of safety systems within the automotive industry heavily relies on the ability to perceive the environment. This is accomplished by using measurements from several different sensors within a sensor fusion framework. One important part of any system of this kind is an accurate model describing the motion of the vehicle. The most commonly used model for the lateral dynamics is the single track model, which includes the so-called cornering stiffness parameters. These parameters describe the tire-road contact and are unknown and even time-varying. Hence, in order to fully make use of the single track model, these parameters have to be identified. In the paper [58] we provide a method for recursive identification of the cornering stiffness parameters to be used on-line while driving. The method has been evaluated on real data.

Recursive system identification is also the topic studied in [51], but in this case for aircraft applications. A recursive frequency domain method has been evaluated on simulated data from the Gripen aircraft. In particular, the influence of system disturbances due to turbulence has been studied and it is shown that such disturbances must be considered when the uncertainty of the estimated parameters is estimated. System identification for the Gripen aircraft has been studied also in [52]. Some characteristic features of this identification problem is that the system is nonlinear and unstable and that the input and output signals have been measured in closed-loop conditions. In [52], the prediction-error method is used for the parameter estimation and the accuracy of this method has been investigated for a couple of different predictor choices. Both simulations and real flight test data have been used here.

2.5 Nonlinear Systems

2.5.1 Using Particle Filtering

The paper [40] reviews the authors' recently developed algorithm for identification of nonlinear state-space models under missing observations and extends it to the case of unknown model structure. To be specific, the nonlinear state-space model is in the following form,

$$x_{t+1} = f_t(x_t, u_t, \theta) + g_t(x_t, u_t, \theta)v_t \tag{2.1a}$$
$$y_t = h_t(x_t, u_t, \theta) + e_t \tag{2.1b}$$

In order to estimate the parameters in a state-space model, one needs to know the model structure and have an estimate of the states. If the model structure is unknown, an approximation of it is obtained using radial basis functions centred around a maximum a posteriori estimate of the state trajectory. Hence, the model in (2.1) is approximated using radial basis functions as follows,

$$x_{t+1} = \sum_{i=1}^{I_x} h_i \rho_i(x_t, u_t, c_i, \sigma_x) + Ax_t + Bu_t + w_t$$
$$y_t = \sum_{i=1}^{I_y} g_i \gamma_i(x_t, u_t, d_i, \sigma_y) + Cx_t + Du_t + v_t$$

where $\rho_i(\cdot)$ and $\gamma_i(\cdot)$ are the radial basis functions. A particle filter approximation of smoothed states is then used in conjunction with the expectation maximization (EM) algorithm for estimating the parameters. The proposed approach is illustrated using data collected from a continuously stirred tank reactor (CSTR).

2.5.2 Block-structured Models

Many nonlinear systems can be described, at least approximately, using block-structured models. These types of models consist of interconnected linear time-invariant submodels and static nonlinearities and have been studied for a long time in the system identification community.

At the SYSID symposium in St Malo an invited session was created around a benchmark problem with Hammerstein structure, [73]. Several suggested solution methods were contributed to this session, which gives an overview of how the problem can be handled and an assessment of pros and cons of the options.

A particular method to handle Hammerstein problem was suggested by E. W. Bai in 2000. We revisit that method and supply a number of insights into the nature of the method in [82] and [23].

2.5.3 Nonlinearity Detection

Many real-life systems are nonlinear but despite that, it is common to estimate linear approximate models of them from measured input and output data. The validity of such an approximate model depends on the operating region for the input signal, as well as how nonlinear the system is. It seems that it would be useful to have a data-based method for detection of nonlinearities in a system. For example, nonlinearity detection is an important topic since many system identification methods and results only are reliable if both the model and the true system are linear, i.e., they should only be used if a reliable nonlinearity test has been used on the available dataset. A method for nonlinearity detection has been proposed in [36]. In this approach, importance weighting is used to mimic the effect of a changed input distribution which, if the system is nonlinear, causes a higher variability in an estimated and validated linear model than what can be explained by measurement noise. The method has been evaluated in numerical examples with good results, except for some resonant nonlinear systems where the nonlinearities seem to be harder to detect.

2.6 Moment-based Estimation using Quantized Data

Consider a discrete time signal

$$y(t) = s(t;\theta) + e(t)$$

modeled as a signal $s(t;\theta)$ in noise $e(t)$, that is only available after quantization as $q(t)$. Many methods in system identification rely on either minimizing the variance

$$\mathrm{Var}\Big(y(t) - s(t;\theta)\Big)$$

or subspace decompositions of the covariance matrix of a vector valued observation $y(t)$. In both cases, it is important to understand the consequence of quantization and possible mitigation approaches. Just replacing $y(t)$ with $q(t)$ might give unexpected results.

One revealing result is presented in the papers [43, 13]. The variance of

$$q = s(\theta) + e$$

for a Gaussian noise (GN) $e \in N(0,\sigma)$ is given by

$$\mathrm{E}q^2 = s^2(\theta) + \sigma^2 + \frac{\Delta^2}{12} + \sum_{k=1}^{\infty} (-1)^k e^{\frac{-2k^2\pi^2\sigma^2}{\Delta^2}} \left[\left(4\sigma^2 + \frac{\Delta^2}{k^2\pi^2}\right)\cos\left(2k\pi\frac{s(\theta)}{\Delta}\right) + \frac{2\Delta s(\theta)}{k\pi}\sin\left(2k\pi\frac{s(\theta)}{\Delta}\right)\right]$$

The first two terms correspond to unquantized data. The third term is what is obtained using the additive uniform noise (AUN) approximation of quantization with level Δ. The remaining terms correspond to aliasing similar to Poisson's summation formula in sampling. Since this term is signal dependent, any estimation based on the second order moment of $q(t)$ will be biased.

One remedy is dithering, where an artificial dithering noise (DN) $d(t)$ is added before the quantization. This is for instance possible when quantization is due to communication constraints. With a properly designed dithering noise, the variance becomes

$$\mathrm{E}q^2 = s^2(\theta) + \underbrace{\sigma^2}_{\text{GN}} + \underbrace{\mathrm{E}d^2}_{\text{DN}} + \underbrace{\frac{\Delta^2}{12}}_{\text{AUN}}$$

Now, the variance is not signal dependent. The price paid for this is a decreased signal to noise ratio.

2.7 Continuous Time Models

Identification of continuous time (CT) models from discrete time measurements, either of output error type

$$y(t) = \frac{B(p)}{F(p)}u(t) + e(t)$$

or time series models of ARMA type

$$y(t) = \frac{C(p)}{A(p)}e(t)$$

is a much studied problem. Here p is the differentiation operator, e is white noise, u is the input and y is the output. Methods may employ explicit sampling procedures, or use special filtering techniques. The paper [10] contains a study how to estimate an CT ARMA model by creating an approximation of the CT Fourier transform from the DFT of the output.

In [55] different Matlab implementations of techniques to estimate CT output error models are studied and compared. It is shown that properties of the unsampling operation `d2c` plays a key role both algorithmically and conceptually. It is also shown that the variation in quality over different realisations is substantial (and larger the model uncertainty would indicate), so it is not easy to draw any definite conclusions about which approach is "best".

2.8 Miscellaneous

Time-Delay Estimation has been studied in [7]. A particular suggested method for estimation of the phase-shift in the transfer function is analysed. It is suggested how some annoying drawbacks with these methods can be avoided.

The "traditional" triennial update report on the progress of the Matlab System Identification Toolbox was presented at the SYSID meeting in St Malo, [56]. The focus this time was on progress of the GUI and Simulink functionalities.

In a development of the DWO approach described in earlier annual reports, confidence intervals for point-wise nonparametric regression estimates were developed, see [48].

Chapter 3

DAE models

Differential-algebraic equation (DAE) models consist of a mixture of equations with or without derivatives. They typically occur when using modern modeling tools where submodels from model libraries are put together. The individual submodels are often state-space models, but the interconnections add algebraic constraints. A general mathematical description is

$$F(\dot{x}, x, u) = 0 \tag{3.1}$$

where x is a vector of physical variables and u is a vector of inputs. Typically the vector x can be split in two set of variables, x_1 and x_2 so that (3.1) can be rewritten

$$\dot{x}_1 = F_1(x_1, x_2, u, \dot{u}, \ldots) \tag{3.2}$$

$$0 = F_2(x_1, x_2, u, \dot{u}, \ldots) \tag{3.3}$$

The transformation may require differentiations of some components of (3.1) which accounts for the possible presence of derivatives of u. There are many structural questions for DAE models in particular when uncertainties in the original model (3.1) make different forms of (3.2) and (3.3) possible.

3.1 Well-posedness and Numerical Properties of Models

In [2] an investigation of properties of DAE models with uncertainties is made. The main theme of the thesis is to analyze how the uncertainty in the solution to a DAE depends on the uncertainty in the equation. In particular, uncertainty in the leading matrix of linear DAEs leads to a new kind of singular perturbation, which is referred to as *matrix-valued singular perturbation*. Although it is a natural extension of existing types of singular perturbation problems, this topic has not been studied in the past. As it turns out that assumptions about the equations have to be made in order to obtain well-posedness, it is stressed that the assumptions should be selected carefully in order to be realistic to use in applications. Hence, it is suggested that any assumptions (not counting properties which can be checked by inspection of the uncertain equations) should be formulated in terms of coordinate-free system properties. In the thesis, the location of system poles has been the chosen target for assumptions.

A large part is devoted to the study of uncertain DAEs and the associated matrix-valued singular perturbation problems. Only linear equations without forcing function are considered. For both time-invariant and time-varying equations of nominal differentiation index 1, the solutions are shown to converge as the uncertainties tend to zero. For time-invariant equations of nominal index 2, convergence has not been shown to occur except for an academic example. However, the thesis contains other results for this type of equations, including the derivation of a canonical form for the uncertain equations.

These insights into the structure of DAE models has led to the formulation of a new index closely related to the strangeness index (the strangeness index is a fundamental concept in DAE theory). Basic properties of the strangeness index are shown to be valid also for the new index. The definition of the new index is conceptually simpler than that of the strangeness index, hence making it potentially better suited for both practical applications and theoretical developments. Parts of this work was also presented in [76].

3.2 Stochastic Dynamic Systems on Manifolds

DAE models can be interpreted as differential equations on manifolds and vice versa. In [77] this fact is utilised to treat state estimation problems. It is shown that robust state estimation for states evolving on compact manifolds is achieved by employing a point-mass filter. The proposed implementation emphasizes a sane treatment of the geometry of the problem, and advocates separation of the filtering algorithms from the implementation of particular manifolds.

3.3 Algebraic Manipulation of Polynomial DAE Models

Many control problems require elimination of variables. To compute the input-output relation of a DAE model

$$F(\dot{x}, x, u) = 0, \quad y = h(x, u)$$

can for instance be seen as the elimination of x. In continuous time there are algorithms by Ritt and Seidenberg that allow a systematic elimination of variables in polynomial DAE models.

Starting, for instance with the equations

$$\underbrace{\ddot{y} + uy}_{p_1} = 0, \quad \underbrace{\dot{y}^2 + u}_{p_2} = 0$$

one can differentiate and subtract to yield

$$p_3 = 2\dot{y}p_1 - \dot{p}_2 = 2\dot{y}(\ddot{y} + uy) - (2\dot{y}\ddot{y} + \dot{u}) = 2uy\dot{y} - \dot{u}$$

The system

$$2uy\dot{y} - \dot{u} = 0, \quad \dot{y}^2 + u = 0$$

is equivalent to the original one if $\dot{y} \neq 0$. In a similar manner $\dot{y}$ and y are eliminated to give a differential equation in u.

If one interprets the dots as time shifts, a similar procedure works in discrete time. The relation

$$\underbrace{\ddot{y} + uy}_{p_1} = 0, \quad \underbrace{\dot{y}^2 + u}_{p_2} = 0$$

is then interpreted as

$$y(t-2) + u(t)y(t) = 0, \quad y(t-1)^2 + u(t) = 0$$

Now

$$p_3 = \ddot{y}(\ddot{y} + uy) - (\ddot{y}^2 + \dot{u}) = uy\ddot{y} - \dot{u}$$
$$p_4 = p_3 - uyp_1 = -\dot{u} - u^2y^2$$

The elimination in discrete time becomes more complicated because the product rule for differentiation does not hold for shifts. A generalization of the Ritt-Seidenberg algorithm to discrete time becomes possible however, as described in [61]. This reference also describes an application to identification.

Chapter 4

Sensor Fusion

Highlights of the year are:

- The Ph. D. thesis of Per-Johan Nordlund [1].
- The Licentiate theses of Christian Lundquist [4] and Per Skoglar [6].
- Best student paper award at the IEEE International Conference on Ultra-Wideband held in Vancouver, Canada, 2009 with the paper [46] by Jeroen Hol et al.
- The scientific publications, including the journal papers [21, 13, 19, 11, 12, 20, 9] and the conference papers [57, 72, 68, 32, 59, 41, 74, 46, 67, 43, 75, 66, 24, 53].

4.1 Project Overview

Our research in sensor fusion covers the whole chain of problems, from sensors to applications, as illustrated in Figure 4.1:

- *Sensor and dynamic motion models*
  - *Sensor modeling* is focused on inertial measurement units (IMU) and using cameras as sensors. The problems involve sensor error modeling, outlier detection and measurement uncertainty assessment.
  - *Sensor-near signal processing* problems needed between the sensors and the sensor fusion block are also essential.

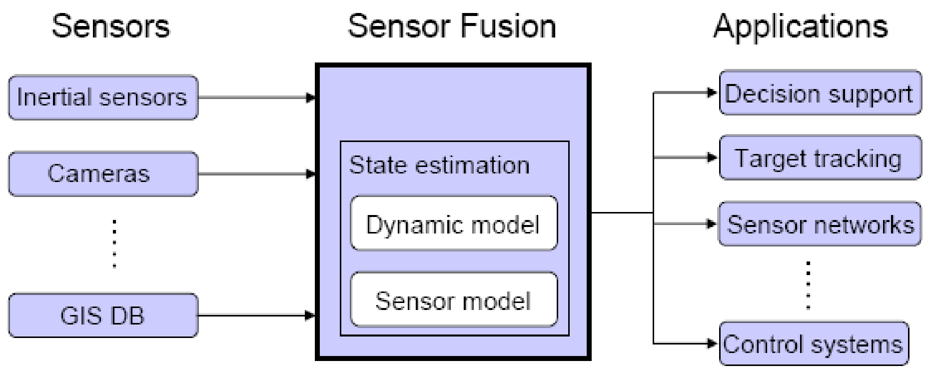


Figure 4.1: Structure of a sensor fusion system and this chapter.

- *Modeling for state estimation*, including kinematic and dynamic models for the applications below. The field tests we are working on involve power measurements from received radio, acoustic, seismic and magnetic waves.

- *State estimation*
  - *Particle filtering* The theoretical research focuses on obtaining scalable and real-time algorithms for sensor fusion applications, where marginalization is the key tool.
  - Detection, localization and tracking in *sensor networks*.
  - *Target tracking* problems.

- *Sensor fusion applications*
  - *Localization and tracking.* The vision and mission are to position everything that moves. We have applications to aircraft, rockets, cars, surface ships, underwater vessels, film cameras, cellular phones and industrial robots. One leading theme is to consider cameras and Geographical Information Systems (GIS) as standard sensors in sensor fusion. A technical driver is to backup, support or replace GPS in critical integrated navigation systems. In some cases, the (extended) Kalman filter is used in our application, but in particular when GIS are used, the particle filter and marginalized particle filter mentioned above are applied.

– *Simultaneous localization and mapping (SLAM)*. Our goal is to develop full 3D SLAM running on UAVs (SAAB, FOI).

– *Situation awareness* and detection algorithms. In particular, collision mitigation and avoidance systems for cars (Volvo) and aircrafts (SAAB).

The current funding comes from Swedish Research Council (VR), MOVIII (SSF excellence center), NFFP decisions based on uncertain data, NRFP fusion of IMU and GPS in rockets, ARCUS (TAIS) path planning of UAVs, FOCUS (VINNOVA institute excellence center): sensor networks, IVSS Sensor Fusion Systems.

4.1.1 The SEFS Project

For driver assistance systems, a thorough perception of the environment has become very important. The SEFS project is part of the Swedish IVSS program. The project focuses on methods and architectures for fusion of sensor data from typically automotive sensors such as radar and vision systems. The objective of the work is to determine a consistent representation of the environment of the ego vehicle based on different sensor observations. The perception of the environment includes detecting, tracking and classifying surrounding objects as well as recognizing lanes and observing the host vehicle's position on the road. From the sensors, observations are received mainly on a detection level.

In order for the fusion algorithm to determine how to combine information originating from several different sensors, also including previous knowledge, it relies on two types of statistical models. One to describe the information in observations coming from the sensors, i.e., measurement or sensor model, and the other to model how the quantities of interest behave as a function of time, i.e., process or motion model. How well both these models describe the true nature of the measurements and the motion of, e.g., vehicles, will greatly affect the accuracy of the fused result.

The main results are summarized in [24], and include a data fusion structure and architecture, implementations of tracking methods, vehicle and road models, and identification of related parameters.

4.2 Localization and Mapping

4.2.1 Particle Filter SLAM with High Dimensional Vehicle Model

The work in [21] presents a particle filter method closely related to FastSLAM for solving the simultaneous localization and mapping (SLAM) problem. Using the standard FastSLAM algorithm, only low-dimensional vehicle models can be handled due to computational constraints. In this work an extra factorization of the problem is introduced that makes high-dimensional vehicle models computationally feasible. Results using the experimental data from an unmanned aerial vehicle, UAV, (helicopter) are presented. The proposed algorithm fuses measurements from on-board inertial sensors (accelerometer and gyro), barometer, and vision in order to solve the SLAM problem.

4.2.2 Loop Closure Detection for SLAM

An integral part of SLAM is the detection of loop closures, i.e., detecting that the robot has returned to a previously visited location. This problem is addressed using laser range data in [41], with promising results. The proposed method compresses the laser range data using features that describe statistical and geometrical properties of the range scans, e.g., mean range and area covered by the scan.

Features from two scans are compared using a classifier which is learned using AdaBoost. AdaBoost is an iterative machine learning algorithm which builds classifiers by concatenating simple, so called “weak”, classifiers. Using the learned classifier, 85% of the true loop closured can be detected, with just 1% false alarms. Figure 4.2 shows a laser range map resulting from a SLAM experiment where the classifier was used to detect loop closures. The proposed method has possible extensions to 3D loop closure detection and to localization in environments with pre-existing maps.

4.2.3 Ego-motion and Indirect Road Geometry Estimation using Night Vision

The sensors present in modern premium cars deliver a wealth of information. In [72] we illustrate one way of making better use of the sensor information already present in modern premium cars. More specifically, it is shown how

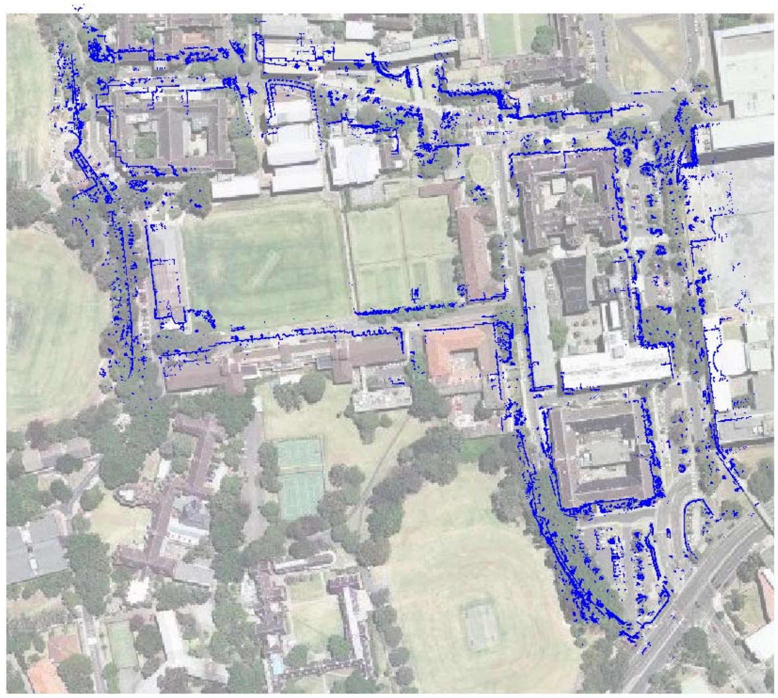


Figure 4.2: The laser range map resulting from the SLAM experiment.

a far infrared (FIR) camera can be used to enhance the estimates of the vehicle ego-motion and indirectly the road geometry in 3D. The FIR camera is primarily intended for pedestrian detection. The solution is obtained by solving a suitable sensor fusion problem, where we merge information from proprioceptive sensors with the FIR camera images. In order to illustrate the performance of the proposed method we have made use of measurement sequences recorded during night-time driving on rural roads in Sweden. The results in [72] clearly illustrate that the FIR images can be used to improve the ego-motion estimation.

4.3 Marginalized Particle Filtering

4.3.1 The Marginalized Auxiliary Particle Filter

In [39] we are concerned with nonlinear systems subject to a conditionally linear, Gaussian sub-structure. This structure is often exploited in high-dimensional state estimation problems using the marginalized (aka Rao-Blackwellized) particle filter. The main contribution in [39] is to show how an efficient filter can be derived by exploiting the conditionally linear, Gaussian sub-structure within the auxiliary particle filter. Based on a multi-sensor aircraft tracking example, the improved performance of the proposed filter over conventional particle filtering approaches is demonstrated.

4.4 Target Tracking

4.4.1 On Information Measures based on Particle Mixture for Optimal Bearings-only Tracking

The paper [74] considers a target tracking scenario where a moving observer with a bearings-only sensor is tracking a target. The tracking performance is highly dependent on the trajectory of the sensor platform, and the problem is to determine how it should maneuver for optimal tracking performance. The problem is considered as a stochastic optimal control problem and two sub-optimal control strategies are presented based on the information filter and the determinant of the information matrix as the optimization objective.

Using the determinant of the information matrix as an objective function is equivalent to using differential entropy of the posterior target density when it is Gaussian. For the non-Gaussian case, an approximation of the differential entropy of a density represented by a particle mixture is proposed. Furthermore, a gradient approximation of the differential entropy is derived and used in a stochastic gradient search algorithm applied to the planning problem.

4.4.2 Road Target Tracking with an Approximative Rao-Blackwellized Particle Filter

The problem of bearings-only road target tracking is considered in [75]. Information about the road network is used to improve the tracking performance and an approach based on the Rao-Blackwellized particle filter is proposed to reduce the dimension of the state space treated by the particle filter. Furthermore, it is also shown how a model of the probability of detection can be used to improve the estimation performance further by drawing conclusions from non-detections.

4.4.3 Improved Target Tracking with Road Network Information

The trackers for ground targets can benefit much from a priori information like road maps and terrain information. The algorithms employed for such problems use multiple models for accommodating different target motion characteristics such as on-road or off-road. The current multiple model particle filters that solve target tracking problem with road network information use a variable number of particles in each mode which changes according to the posterior mode probabilities. This scheme has harmful effects in terms of both performance especially when sharp mode switchings occur and of computation. In the work [68], another particle filter algorithm proposed in the literature is applied to the problem. The algorithm uses user-selected constant number of particles in each mode, whose advantages are shown using simulations.

4.4.4 Distributed Target Tracking with Propagation Delayed Measurements

An increasing trend in sensor networks is to use many cheap and low quality sensors to accomplish the tasks that were done in the past using few expensive and high-quality sensors. In such scenarios, the signal propagation delays between the target and the sensors start to become more and more important. This is especially the case when the target speed approaches the propagation speed of the signals (e.g., sound) in the propagation medium (air, in the case of sound).

A deterministic sampling based estimation algorithm was proposed from our group in the previous year in order to compensate for the unpredictable effects of propagation delays in the tracking filters. This year, the follow-up work in [67] generalizes the delay compensation algorithm proposed in the previous year to multiple sensor observations. A distributed estimation framework where the local estimates are communicated among the sensors is adopted. Each sensor runs the local delay compensation algorithm and their state estimates are corrected by other sensors' estimates using a consistent measurement update derived from the largest ellipsoid algorithm.

Figure 4.3: Left: example of an unmanned aerial vehicle, here a RQ-7 Shadow UAV. Right: example of a gyro-stabilized sensor gimbal with an infrared sensor. The gimbal has two actuated DOFs, pan and tilt.

4.5 Licentiate Thesis: Planning Methods for Aerial Exploration and Ground Target Tracking

In [6] an unmanned airborne surveillance system equipped with electro-optical vision sensors is considered. The aim is to increase the level of autonomy and improve the system performance by the use of planning methods for aerial exploration, search and target tracking. In Figure 4.3 an example of a UAV and a sensor payload are shown.

The general UAV surveillance problem is very complex and suboptimal approaches are necessary. A general planning framework is proposed and the planner contains a high-level scheduler and a number of planning modes. Each mode consists of planning modules that solve smaller sub-tasks and in [6] a number of these modules are developed. In particular, two major approaches are proposed; information based planning, and Bayesian target search. In addition, the on-road target tracking problem is treated and an algorithm based on the particle filter is presented.

Simulation Example

The surveillance scenario considered here is to survey a road network and search for, initially unknown, road vehicles. When vehicles are discovered they should be tracked simultaneously, and furthermore the exploration of the roads and the search for new vehicles should continue.

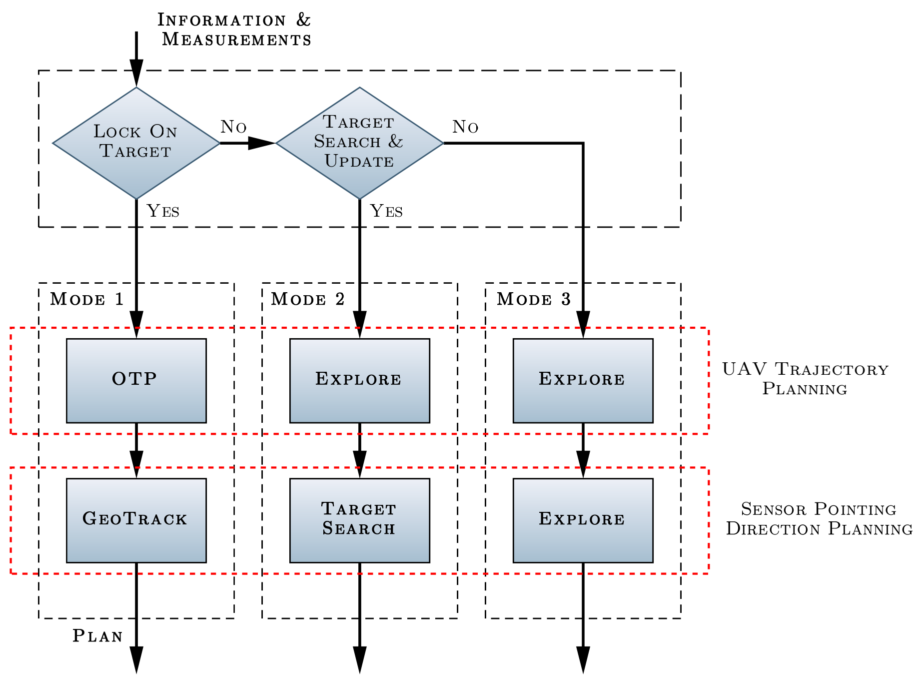
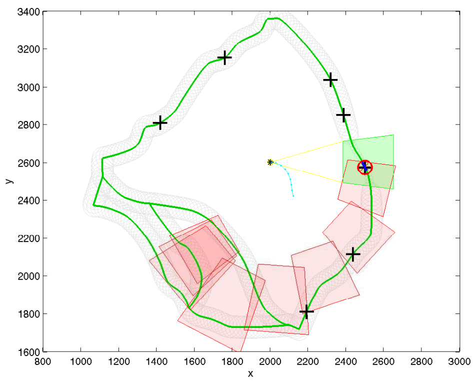
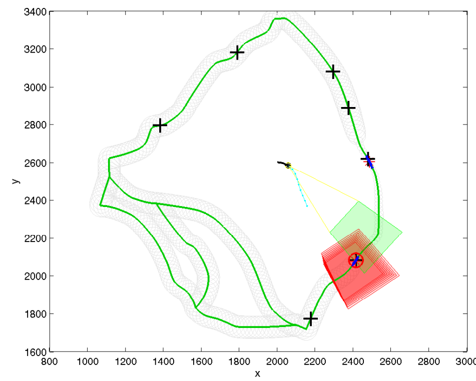


Figure 4.4: Example of a UAV surveillance planning framework for planning of the flight route and the pointing direction of the vision sensor.

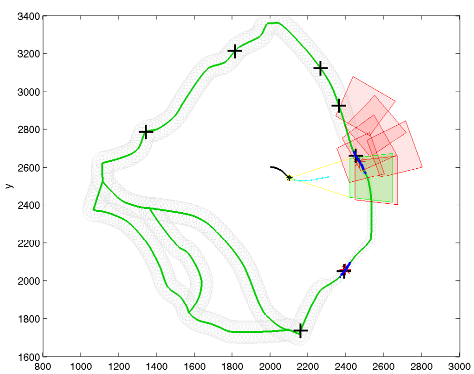
A task of the planner is to control the flight path of the UAV and the pointing direction of the pan/tilt camera such that the performance of the tracking and exploration is as good as possible. The planning framework that is applied to this problem is shown in Figure 4.4 and it consists of three planning modes. Planning mode 1 is active when a target is discovered or re-discovered. Then an optimal UAV trajectory planning (OTP) is performed and the sensor points in the target direction (GeoTrack). Mode 2 computes plans for the search and measurement update of known targets and mode 3 creates plans for how the roads should be explored and new targets can be found. During the mission, the planner switches between these modes. Essentially the system is alternating between updating known targets and exploring the roads and searching for new targets. A number of snapshots from a simulation run are shown in Figure 4.5.



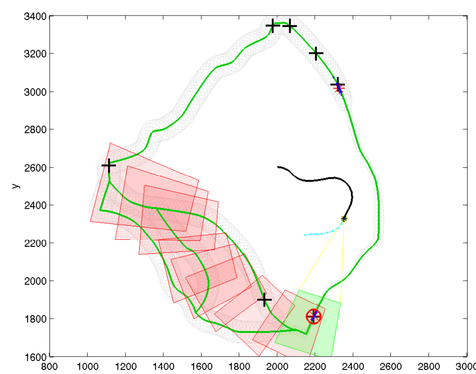
(a) t = 0. A search plan for some roads is created. One target is detected immediately (circle).



(b) t = 2. Detection of a second target. Note that the ellipses on the road shrink as the road is explored.



(c) t = 4. A search plan for re-discovery of the first target is created and the target is detected again (not shown).



(d) t = 20. Target 2 is detected again and a search plan for the unexplored roads is created.

Figure 4.5: Simulation snapshots of a road surveillance scenario. Solid and dotted line: past and future path of the UAV path, respectively. Squares: current and future sensor footprint on the ground. Connected lines: the road network. Ellipses along the roads: the "quality" of the exploration, the smaller the ellipses are, the better the road segments are explored.

4.6 Licentiate Thesis: Automotive Sensor Fusion for Situation Awareness

The use of radar and camera for situation awareness is gaining popularity in automotive safety applications. In the licentiate thesis [4] situation awareness consists of accurate estimates of the ego vehicle's motion, the position of the other vehicles and the road geometry. By fusing information from different types of sensors, such as radar, camera and inertial sensor, the accuracy and robustness of those estimates can be increased.

A new formulation for the rather well studied problem of integrated road geometry estimation and vehicle tracking is presented. This framework improves the vision estimate of the road geometry by fusing it with radar measurements of the leading vehicles and information from proprioceptive sensors (e.g., velocity or yaw-rate sensors). Hence, if the leading vehicles can be accurately tracked, their motion can be used to improve the road geometry estimates. Furthermore, a single track dynamic model of the ego vehicle allows to further refine the estimates by incorporating several proprioceptive sensor measurements from the CAN bus. The so-called cornering stiffness parameters of the single track model describe the tire-road contact and are unknown and even time-varying. Hence, in order to fully make use of the single track model, these parameters have to be identified. In [58] a method for recursive an on-line identification of the cornering stiffness parameters is provided.

A good polynomial approximation of the shape of the road is given by

$$y = l + \delta_r x + \frac{c_0}{2} x^2 + \frac{c_1}{6} x^3$$

in an ego vehicle fixed coordinate frame (with x in longitudinal direction and y in lateral direction). The angle between the longitudinal axis of the vehicle and the road lane is δ_r. The curvature parameter is denoted by c_0 and the offset between the host vehicle and the white lane marking is denoted by l.

The road curvature estimation using the sensor fusion approach (denoted fusion 1) is compared to a similar approach (denoted fusion 2) in Figure 4.6. An important difference between the two approaches is that the float angle β is modeled in fusion 1, hence, the information about the host vehicle motion is utilized in the estimation process. Furthermore, a road aligned coordinate frame is used in fusion 2.

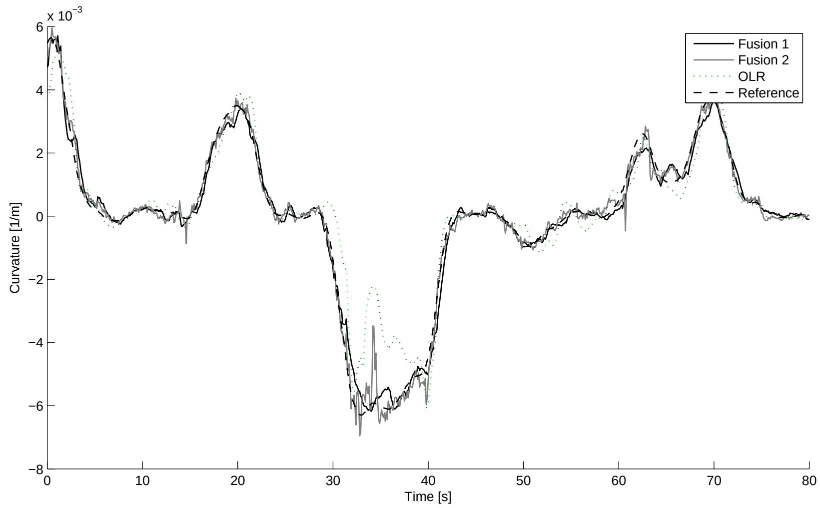
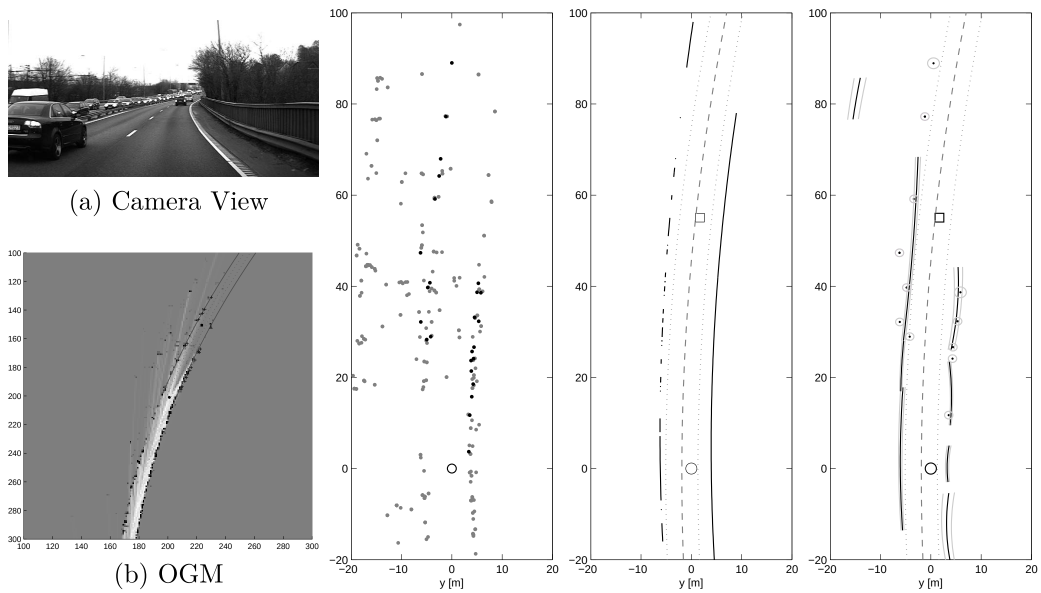


Figure 4.6: Results from the two fusion approaches (solid black and gray lines) and the optical lane recognition, (OLR, dotted line), showing the curvature estimate $\hat{c}_0$. As can be seen the curvature estimation can be improved by taking the other vehicles (gray line) and the host vehicle's driven curvature in account (solid black line). The dashed line is the reference curvature.

Moreover, information already present in the radar detections concerning stationary targets along the road are used to provide a reliable estimate of the free space in front of a moving vehicle. Three conceptually different methods to estimate stationary objects or road borders are compared. The results are illustrated with the traffic situation shown in Figure 4.7a with the associated radar measurements in Figure 4.7c.

The first method considered is occupancy grid mapping (OGM), which discretized the map surrounding the ego vehicle and the probability of occupancy is estimated for each grid cell. More details about the OGM are given in [107]. The resulting bird's eye view is shown in Figure 4.7b. The second method, thoroughly described in [57], applies a constrained quadratic program (QP) in order to estimate the road borders. The problem is stated as a constrained curve fitting problem. The result using a linear model containing four parameters is shown in Figure 4.7d. The third method, described in [59], associates the radar measurements to extended stationary objects and tracks them as extended targets. The stationary objects are represented as points, with sources such as delineators or lampposts, or lines, where measurements stem from, e.g., guard rails or concrete walls. For the given example the estimated points and lines are shown in Figure 4.7e. Finally, the estimated road shape according to (4.6) is illustrated by the dashed gray lines in Figure 4.7b, (d) and (e).



(a) Camera View

(b) OGM

(c) Measurements (d) Constrained QP (e) Ext. Targets

Figure 4.7: The camera view of a traffic situation is shown in Figure (a). Figure (c) shows the bird's eye view of the radar measurements, and Figure (b), (d) and (e), the estimated stationary objects along the road. The circle is the ego vehicle, the square is the tracked vehicle in front and the dashed gray lines illustrates the estimated road curvature.

Chapter 5

Robotics

5.1 Introduction

The research within the robotics area is to a large extent carried out in close cooperation with ABB Robotics and ABB Corporate Research. From 2008 the collaboration is carried out within the Industry Excellence Center LINK-SIC (Linköping Center for Sensor Informatics and Control) supported by VINNOVA. The overall aim of the center is to generate results that are of both high scientific quality and industrial relevance.

5.2 Model Based Control

The performance requirements in terms of cycle time and accuracy of modern industrial robots require carefully designed control methods based on accurate dynamical models. Due to a desire to reduce cost and weight, each new robot generation offers new challenges since the robots contain more of mechanical elasticities.

Control of industrial robots has been an active research area for many years, and a large number of design methods have been proposed. There is still a gap between the academic research and the industrial practise, and it is hence an ambition in this research area to bridge over this gap. This is done by proposing industrial relevant benchmark problems to the academic world. One such example is presented in [18], where a four-mass flexible system is proposed as a SISO benchmark control problem, and a number of proposed solutions are evaluated.

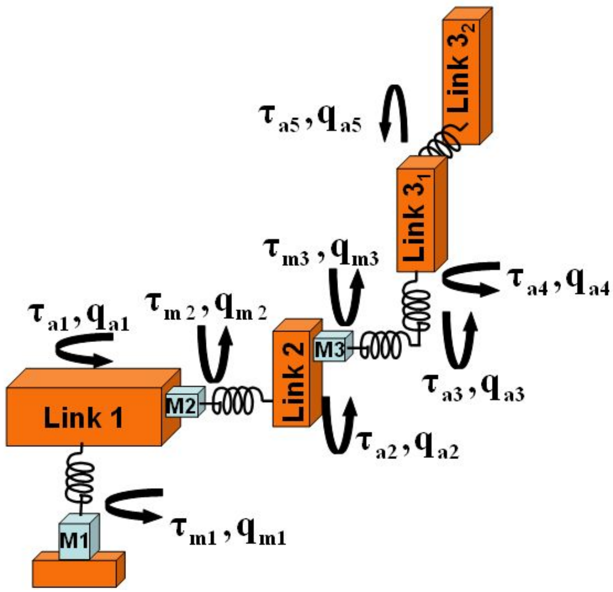


Figure 5.1: An extended flexible joint dynamic model with eight degrees of freedom.

As a result of increased mechanical elasticity it has turned out that the conventional flexible joint model is no longer sufficient to describe a modern industrial robot with the desired accuracy, and instead an extended flexible joint model has been proposed, see Figure 5.1. This model makes the computation of the inverse dynamics considerably more difficult since it involves solving a high index differential-algebraic equation (DAE). In [63] it is shown how this problem can be treated for robot models of realistic complexity.

5.3 Sensor Fusion

Another consequence of the increased mechanical flexibility of modern industrial robots is a need to develop methods to estimate the position and orientation of the robot tool. Therefore there is an interest in applying sensor fusion methods to industrial robots. This is a very challenging task since the dynamic model of an industrial robot is very complex. Some examples of attempts to treat this problem are given in [44] and [84].

5.4 Iterative Learning Control

Since an industrial robot typically carries out operations repeatedly, this can be utilised in order to iteratively improve the accuracy of the control system. This control method, denoted iterative learning control (ILC), has been an active research area within the group for several years.

The interest during the recent years has been concentrated to ILC applied to robots containing mechanical flexibilities. The large challenge in such a case is that the controlled variables are different from the measured variables. In standard industrial robots the controlled variables are the position and the orientation of the tool, while the measured variables are the angles of the motors that generate the motion. This situation implies that good performance when studying the measured variables does not necessarily imply good performance of the controlled variables.

One approach to handle this problem is to estimate the position and orientation of the tool and use the estimated variables in the ILC algorithm. In [79] this idea is studied using a two-mass SISO model, where it is found that the performance is improved considerably by using an estimate of the controlled variable. In [80] the approach is generalised to a two-link nonlinear flexible manipulator and results from [44] are used to generate the relevant state estimates. The research has also resulted in a framework for observer based ILC, presented in [81]. The framework can be used to analyse the control performance using different types of ILC algorithm and different ways to estimate the controlled variables, also including additional sensors.

Chapter 6

Optimization for Control

6.1 Introduction

The research in optimization for control is currently focused on optimization algorithms for robustness and stability analysis of control systems, applied optimization in control, and model reduction.

6.2 Optimization Algorithms for Robustness Analysis

In this project we study how to construct efficient Interior-Point (IP) algorithms for Semidefinite Programs (SDPs) derived from the KYP (Kalman-Yakubovich-Popov) lemma. There are several applications for such SDPs in control and signal processing, e.g., filter design, robust control analysis, Lyapunov function search, etc.

In industrial applications the optimization problems often get so large that standard SDP solvers cannot handle them. The computational complexity stems from the cost of assembling and solving the equations for the search directions in the IP algorithms.

An approach to reduce the computational cost is presented in [22]. The method is based on reducing the number of variables in the dual problem by eliminating equality constraints in an efficient way. Another approach based on dual decomposition with application to mixed H_2/H_∞-design is presented in [38, 86].

Work on how to formulate the stability margins clearance criterion for flight control laws as a convex optimization problem is presented in [69, 112].

6.3 The Modelling Language YALMIP

An important part of optimization based control and systems theory is easily used tools and frameworks for algorithm development. The optimization modelling language YALMIP, implemented as a free Matlab toolbox, has been continuously developed and extended during the year. The current focus in the development is geared towards robust optimization with applications in Model Predictive Control (MPC). The toolbox now features support for automatically deriving certain counterparts of optimization models involving uncertainty, thus allowing us to formulate and solve worst-case and minimax problems easily. These additions to the toolbox have been extensively exploited when deriving new MPC algorithms for linear parameter-varying systems [30, 31].

While the robust optimization module in YALMIP still is in development, the sum-of-squares functionality has reached a mature state and was presented in a special issue on Positive Polynomials in Control in IEEE Transactions on Automatic Control [17]. Another functionality in the modelling language, so called automatic dualization, was presented in [16]. YALMIP has now also been incorporated to the GloptiPoly toolbox, an extension which was described in [15].

In [62], new applications of bilevel optimization are discussed in the context of analysis of MPC laws. An important part for this work is the incorporation of bilevel modelling and an associated solver in YALMIP.

6.4 Model Reduction

In 2009, Daniel Ankelhed presented his Licentiate thesis [3] on low order controller synthesis using rational constraints. It treats algorithms for designing low-order controllers based on H_∞-synthesis.

The approach used in the thesis is based on formulating the constraint on the maximum order of the plant as a polynomial or rational criterion [93]. By using the fact that this function is non-negative on the feasible set, the problem is reformulated as an optimization problem where the nonconvex criterion function is minimized over a convex set defined by linear matrix inequalities. To solve this optimization problem, two methods have been proposed. The first method is a barrier method and the second one is a method based on a primal-dual framework. These methods have been evaluated on several problems and compared with a well-known method found in the literature. These results were also presented in [27].

Another line of research is initialized in [70]. Here, we are concerned with the identification (or interpolation) of linear parameter-varying (LPV) state-space models. The emphasis is derivation of computationally efficient schemes to optimize system-relevant performance measures of the approximation quality.

An approach for computing upper error bounds for reduced-order models of linear time-varying (LTV) systems is presented in [14]. It is based on a transformation technique of the Hankel singular values using special kind of time-varying, positive-real functions. By applying such time-varying functions, some Hankel singular values can be forced to become equal and constant, so that they can be removed from the model. Two variations of this method are proposed: one for finite-time horizons and the other for infinite-time problems including periodic systems.

Appendix A

Personnel

Lennart Ljung is Professor and head of the Division of Automatic Control since 1976. He was born in 1946 and received his Ph. D. in Automatic Control from Lund Institute of Technology in 1974. He is a member of the Royal Swedish Academy of Engineering Sciences (IVA) and the Royal Swedish Academy of Sciences (KVA). He is an honorary member of the Hungarian Academy of Engineering, and a Foreign Associate of the US National Academy of Engineering (NAE). He is also an IEEE Fellow and an IFAC Advisor, and associate editor of several journals. He has received honorary doctor's degrees from the Baltic State Technical University in S:t Petersburg, Russia (1996), from Uppsala University, Uppsala, Sweden (1998), from l'Université de Technologie de Troyes, France (2004), from the Katholieke Universiteit in Leuven, Belgium (2004) and from Helsinki Institute of Technology (2008). In 2002 he received the Quazza medal from IFAC, in 2003 the Hendryk W. Bode Lecture Prize from the IEEE Control Systems Society, and in 2007 the IEEE Control Systems Field Award.

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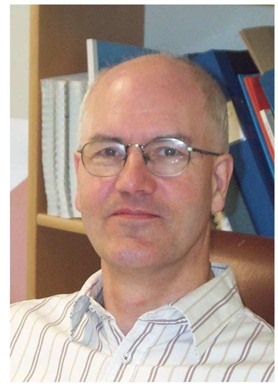

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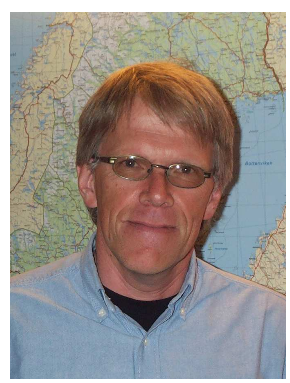

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Thomas Schön is Associate Professor at the Division of Automatic Control. He was born in 1977. He received the Ph. D. degree in Automatic Control in 2006, the M. Sc. degree in Applied Physics and Electrical Engineering in 2001 and the B. Sc. degree in Business Administration and Economics in 2001, all from Linköping University. He has held visiting positions at the University of Cambridge (UK) and the University of Newcastle (Australia). His research interests are mainly within the areas of signal processing, machine learning and system identification and robotics, with applications mainly to the automotive and the aerospace industry.

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Johan Löfberg is the Director of Studies and Assistant Professor at the Division of Automatic Control, and he was born in 1974. He received his M. Sc. in Mechanical Engineering in 1998, his Techn. Lic. in 2001 and his PhD in 2003, all at Linköping University. During 2003 – 2006 he was employed as a Postdoctoral Associate at ETH, Zürich. His research interests are mainly within the area of optimization and model predictive control.

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Umut Orguner is Assistant Professor at the Division of Automatic Control. He was born in 1977. He received B. Sc., M. Sc. and Ph. D. degrees all in Electrical Engineering from Middle East Technical University, Ankara, Turkey in 1999, 2002 and 2006, respectively. Between 1999 and 2007, he was with the Department of Electrical and Electronics Engineering at the same university as a teaching and research assistant. His research interests include estimation theory, multiple-model estimation, target tracking and information fusion.

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David Törnqvist is Assistant Professor at the Division of Automatic Control. He was born in 1979. He received his M. Sc. in Communication and Transport Engineering in 2003, his Techn. Lic. in 2006 and his Ph. D. in 2008 all from Linköping University. His main research interests are in signal processing and sensor fusion.

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Erik Wernholt is Assistant Professor at the Division of Automatic Control. He was born in 1975. He received his M. Sc. in Applied Physics and Electrical Engineering in 2001, his Techn. Lic. in 2004 and his Ph. D. in 2007, all at Linköping University. His research interests are in system identification, mainly for industrial robots.

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Jean Thomas is a Postdoctoral Associate at the Division of Automatic Control. He was born in Minia, Egypt, in 1969. He received his B. Sc. degree in 1991 in Electricial Engineering from Minia University, Egypt, and his M. Sc. degree in Process Control in 1997 from Eindhoven Technical University, The Netherlands. In 2004 he received his Ph. D. degree in Automatic Control from Supelec, France. Since 2005, he is an Associate Professor in Beni-Suef University, Egypt. His research interests include hybrid systems, predictive control and robust control.

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Emre Özkan is a Postdoctoral Associate at the Division of Automatic Control. He was born in 1980. He received B. Sc. and Ph. D. degrees both in Electrical Engineering from Middle East Technical University, Ankara, Turkey in 2002 and 2009, respectively. Between 2002 and 2009, he was at the Department of Electrical and Electronics Engineering at the same university as a teaching and research assistant. His research interests include estimation theory, parameter estimation, target tracking and information fusion.

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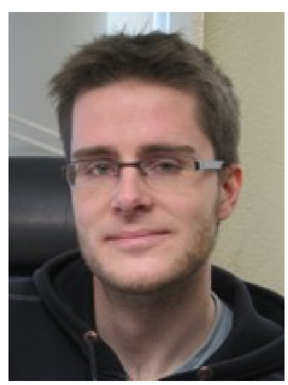
Daniel Ankelhed is a Ph. D. student at the Division of Automatic Control. He was born in 1980. He received his M. Sc. in Applied Physics and Electrical Engineering in 2005 and his Techn. Lic. in 2009, both from Linköping University. His main research interest is synthesis of low order H_∞ controllers.



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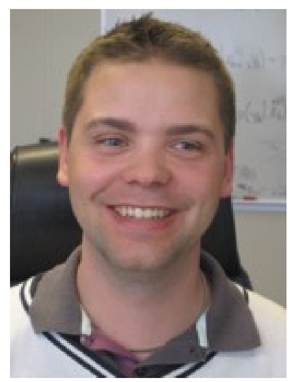

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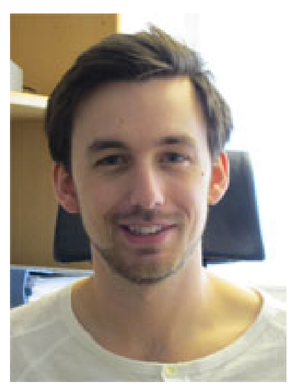

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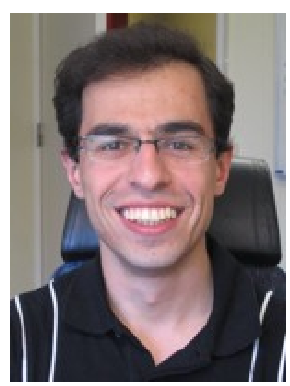

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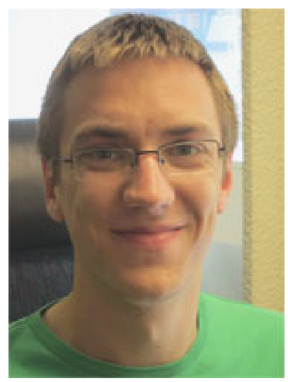

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Sören Hansson is employed as Research Engineer at the Division of Automatic Control on a part time basis, where he is responsible for the laboratory equipment.

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Visitors

John Lygeros Swiss Federal Institute of Technology, Switzerland, visited the division on January 29-30.

Yvo Boers Thales Nederland B.V, Netherlands, visited the division on January 29-30.

Alfio Masi University of Siena, Italy, visited the division between January and June.

Adrian Wills University of Newcastle, Australia, visited the division between June 23 and July 3.

Karl-Henrik Johansson KTH, Stockholm, Sweden visited the division to give a course during September 1-4.

Anders Rantzer LTH, Lund, Sweden, visited the division to give a course during September 1-4.

Roland Toth Delft University of Technology, The Netherlands, visited the division during October 3-10.

Matthijs Spaan Instituto Superior Tecnico, Portugal, visited the division on October 29-30.

Carsten Fritsche Technische Universitat Darmstadt, Germany, visited the division on November 15-28.

Vaclav Smidl Institute of Information Theory and Automation, Czech Republic, visited the division on December 17-18.

Appendix B

Courses

B.1 Undergraduate Courses

M. Sc. (civ.ing.)-program

- *Automatic Control* (Reglerteknik) The basic control course given for all engineering programs. *Contents*: The feedback concept, PID-controllers, Frequency domain design techniques, Sensitivity and robustness, State space models and state feedback controllers, Observers.

  - M Mechanical Engineering. 100 participants. Lecturer: Johan Löfberg.
  - Y, D Applied Physics and Electrical Engineering and Computer Engineering. 120 participants. Lecturer: Lennart Ljung.
  - I Industrial Engineering and Management. 120 participants. Lecturer: Svante Gunnarsson.
  - TB, KB Engineering Biology and Chemical Biology Programs. 45 participants. Lecturer: Thomas Schön.

- *Control Theory* (Reglerteori). For the Applied Physics and Electrical Engineering and Computer Science and Engineering Programs. Multivariable systems, Fundamental limitations in feedback control systems, LQG-control, Loop transfer recovery, Loop shaping methods, Nonlinear systems, Optimal control. 50 participants. Lecturer: Torkel Glad.

- *Automatic Control M, advanced course* (Reglerteknik, fortsättningskurs M). For the Mechanical Engineering Program. Multivariable systems, Nonlinear systems. 20 participants. Lecturer: Svante Gunnarsson.

- *Digital Signal Processing* (Digital signalbehandling). For the Applied Physics and Electrical Engineering and Computer Science and Engineering Programs. Spectral analysis, Filtering, Signal modeling, Wiener and Kalman filtering, Adaptive filters. 90 participants. Lecturer: Thomas Schön.

- *Sensor Fusion* (Sensorfusion). For the Applied Physics and Electrical Engineering and Computer Science and Engineering Programs. Estimation and detection theory, Sensor networks, Linear and non-linear filters, SLAM. 20 participants. Lecturer: Fredrik Gustafsson.

- *Optimal Control* (Optimal styrning). For the Applied Physics and Electrical Engineering and Computer Science and Engineering Programs. The maximum principle, The Hamilton-Jacobi-Bellman equation, Numerical methods for solving optimal control. 30 participants. Lecturer: Anders Hansson.

- *Modelling and Simulation* (Modellbygge och simulering). For the Applied Physics and Electrical Engineering program. Physical system modelling, Bond graphs, Identification methods, Simulation. 60 participants. Lecturer: Erik Wernholt.

- *Industrial Control* (Industriell reglerteknik). For the Applied Physics and Electrical Engineering, Computer Science and Engineering and Industrial Engineering and Management Programs. Numerical control, Binary control and PLCs, Process computers, Model predictive control, Monitoring and applications of digital process control. 60 participants. Lecturer: Martin Enqvist.

- *Real Time Process Control* (Realtidsprocesser och reglering). For the Information Technology Program. Real time systems. PID control. 20 participants. Lecturer: Martin Enqvist.

- *Linear Feedback Systems* (Återkopplade linjära system). For the Information Technology Program. Linear systems, Controllability, Observability, Feedback control. 20 participants. Lecturer: Thomas Schön.

- *Control Project Laboratory* (Reglerteknisk projektkurs) For the Applied Physics and Electrical Engineering and Computer Science and Engineering Programs. Modelling and identification of laboratory processes, Controller design and implementation. 35 Participants. Lecturer: David Törnqvist.

- *Introduction to MATLAB* (Introduktionskurs i MATLAB). Available for several engineering programs. 300 participants. Lecturer: Johan Löfberg

- *Project Work* (Ingenjörsprojekt Y). Develop an understanding of what engineering is all about and how the work is performed. Administration, Planning, Communication, Documentation and presentation of project work. 12 participants. Lecturer: Svante Gunnarsson.

- *Perspectives to Computer Technology* (Perspektiv på datateknik). Project work with focus on computer technology. 6 participants. Lecturer: External.

B. Sc. (tekn.kand.)-program

- *Automatic Control.* Dynamical systems, The feedback principle, Frequency domain analysis and design of control systems, Robustness and sensitivity of control systems, Sampling, Implementation, Some examples of nonlinearities in control systems, Simulation of dynamic systems. 90 participants. Lecturer: Ragnar Wallin.

- *Automatic Control.* Sequential control and logic controllers, A typical industrial control system. 42 participants. Lecturer: Ragnar Wallin.

B.2 Graduate Courses

- *Robust Multivariable Control.* Literature: Zhou, J. C. Doyle and K. Glover, Robust and Optimal Control, Prentice Hall 1995. S. Skogestad and I. Postlethwaite: Multivariable Feedback Control: Analysis and Design, John Wiley and Sons. Lecturer: Anders Helmersson.

- *Nonlinear Systems.* Literature: Lecture notes. Lecturer: Torkel Glad.

- *Target Tracking*. Literature: S. Blackman and R. Popoli, Design and Analysis of Modern Tracking Systems, Artech House, Norwood MA, 1999. Lecturer: Umut Orguner.

Appendix C

Seminars

- *Particle Filter Based State Estimation: Not Always a Mean Thing.* **Yvo Boers**, SR-Engineering, Thales Nederland B.V. January 29, 2009.

- *Modeling Energy Systems — Examples in a Systems Perspective.* **Magnus Karlsson**, Energy systems, IEI, Linköping University. February 12, 2009.

- *Complexity Issues, Validation and Input Design for Control in System Identification.* **Märta Barenthin Syberg**. February 19, 2009.

- *Convex Relaxations with Applications to Robust Control Problems.* **Alfio Masi**, University of Siena, Italy. March 5, 2009.

- *Optimal Placement of Communications Relay Nodes.* **Oleg Burdakov**, MAI, Linköping University. March 12, 2009.

- *Distributed Optimization in Networked Systems — Why? How? Does it work in Practice?* **Björn Johansson**, Automatic Control, KTH. March 19, 2009.

- *On the Behavior of the Conjugate-Gradient Method on Ill-Conditioned Problems.* **Anders Forsgren**. March 27, 2009.

- *Docentföreläsning: Using Parametric Optimization in System Identification and Regression.* **Jacob Roll**, Autoliv. March 30, 2009.

- *Sensor Placement Analysis for Fault Isolation.* **Erik Frisk and Mattias Krysander**, Vehicular Systems, ISY, Linköping University. April 16, 2009.

- *Global Robust Stabilization and Output Regulation by State Feedback for Feedforward Systems and their Applications.* **Tianshi Chen**, Automatic Control, ISY, Linköping University. April 23, 2009.

- *Task Planning and Control of Semi-autonomous Surveillance UGVs.* **Petter Ögren**, Autonomous Systems, FOI. May 7, 2009.

- *MOVIII Seminar — What we don't know about Robotic Aircraft or UAS.* **Rodney Walker**, Queensland University of Technology and Australian Research Centre for Aerospace Automation. May 26, 2009.

- *Probabilistic Techniques for Mobile Robot Navigation.* **Wolfram Burgard**, Albert-Ludwigs-Universität Freiburg, Germany. May 28, 2009.

- *Robots in Manufacturing Research at University West.* **Anna-Karin Christiansson and Mikael Ericsson**, University West, Trollhättan. June 4, 2009.

- *Hardware Implementation of Model Predictive Control.* **Adrian Wills**, University of Newcastle, Australia. June 25, 2009.

- *3-day Course: Distributed and Event-based Control, Lecture 1.* **Anders Rantzer**, LTH. September 2, 2009.

- *3-day Course: Distributed and Event-based Control, Lecture 2.* **Anders Rantzer**, LTH. September 3, 2009.

- *3-day Course: Distributed and Event-based Control, Lecture 3.* **Karl-Henrik Johansson**. September 4, 2009.

- *System Identification of Biochemical Reaction Systems and Realization Theory for Rational Systems.* **Jan van Schuppen and Jana Nemcova**, CWI. September 8, 2009.

- *Model Predictive Control for Hybrid Systems.* **Jean Thomas**, Automatic Control, ISY, Linköping University. September 17, 2009.

- *DIPLECS — Dynamic Interactive Perception-action LEarning in Cognitive Systems.* **Michael Felsberg**, Computer Vision Laboratory, ISY, Linköping University. September 24, 2009.

- *Identification of Linear Parameter-varying Systems: Challenges and Solutions.* **Roland Toth**, Delft University of Technology, The Netherlands. October 8, 2009.

- *Mathematical Modelling of Arteries — Can Biomechanics Predict Arterial Diseases?* **Jonas Stålhand**, Mechanics, IEI, Linköping University. October 15, 2009.

- *Experiences from Gröna Tåget and Future Trends in the Railway Industry.* **Henrik Mosskull**, Bombardier. October 22, 2009.

- *Decision-theoretic Planning under Uncertainty for Active Cooperative Perception.* **Matthijs Spaan**, Institute for Systems and Robotics, Instituto Superior Técnico, Lisbon, Portugal. October 29, 2009.

- *An Analysis of the Optimal Geometries for Localization and Some Problems in Formation Control.* **Adrian Bishop**, KTH. November 5, 2009.

- *Optimal Scheduling in OFDMA under a Control Signaling Cost Constraint.* **Erik G. Larsson**, Communication Systems, ISY, Linköping University. November 12, 2009.

- *High Voltage Direct Current, HVDC.* **Janne Harju Johansson**, ABB. November 17, 2009.

- *Modeling and Simulation Projects at the Mechatronic Group at Chalmers University.* **Jonas Sjöberg**, Chalmers. November 19, 2009.

- *Sensor Fusion for Monitoring of Tire Pressures.* **Rickard Karlsson**, Nira Dynamics. November 26, 2009.

- *Signal Processing Algorithms for Ultra-wide Band Synthetic Aperture Radar.* **Lars Ulander**, FOI. December 3, 2009.

- *Traffic Control: A Case for Scalable Robust Control.* **Ulf Jönsson**, KTH. December 10, 2009.

- *On Combining Distributional Approximations in Bayesian Filtering.* **Vaclav Smidl**, Institute of Information Theory and Automation, Czech Republic. December 17, 2009.

Appendix D

Travels and Conferences

Daniel Ankelhed participated in the 48th IEEE Conference on Decision and Control in Shanghai, China, December 16–18.

Jonas Callmer participated in the 4th Summer School in Simultaneous Localisation and Mapping (SLAM) hosted by the Australian Centre for Field Robotics, University of Sydney, Australia, on January 20–23. He also participated in the 2009 IEEE International Conference on Robotics and Automation, Kobe, Japan, May 12–17.

Martin Enqvist participated in the 15th IFAC Symposium on System Identification, Saint-Malo, France, July 6–8 and in the 18th ERNSI Workshop, Stift Vorau, Austria, September 30 – October 2.

Rikard Falkeborn participated in the 6th IFAC Symposium on Robust Control Design, Haifa, Israel, June 16–18. He also participated in the European Control Conference 2009, Budapest, Hungary, August 23–26.

Torkel Glad participated in the second IFAC meeting on analysis and control of chaotic systems, London, June 22–24.

Karl Granström participated in the 4th Summer School in Simultaneous Localisation and Mapping (SLAM) hosted by the Australian Centre for Field Robotics, University of Sydney, Australia, January 20–23. He also participated in the 2009 IEEE International Conference on Robotics and Automation, Kobe, Japan, May 12–17.

Svante Gunnarsson visited EPFL, Lausanne, Switzerland, April 28–29, participated in the CDIO fall meeting at Turku University of Applied Sciences, Turku, Finland, October 5–7, and participated in 2:a Utvecklingskonferensen för Sveriges Ingenjörsutbildningar, Lund, Sweden, November 2–3.

Fredrik Gustafsson participated in Ph. D. committees in Darmstadt, Kaiserslautern, Delft, Cambridge, and Twente. He also acted as the opponent at KTH. He participated in the 15th IFAC Symposium on System Identification, Saint-Malo, France, July 6–8.

Anders Hansson participated in the COFCLUO technical meeting in Stockholm, Sweden, March 12–13, the 3rd Nordic Optimization Symposium, Stockholm, Sweden, March 13–14, the 1st LCCC workshop in Lund, Sweden, May 28–29, the 6th IFAC ROCOND in Haifa, Israel, June 16-18, the European Control Conference and the EUCA Council meeting in Budapest, Hungary, August 23–26, the COFCLUO technical meeting in Toulouse, France, September 23–25, the Hagander Symposium in Lund, Sweden, December 10, and the 48th IEEE Conference on Decision and Control in Shanghai, China, December 16–18. He also visited Aalborg University, Denmark, September 10–11, Universiy of Siena, Italy, October 20–23, and Lund University, Sweden, November 27.

Roger Larsson participated in the 15th IFAC Symposium on System Identification, Saint-Malo, France, July 6–8. He also participated in the 40th Annual International SFTE Symposium on Flight Test Engineering, Linköping, Sweden, September 7–11.

Fredrik Lindsten participated in the 7th IFAC Symposium on Fault Detection, Supervision and Safety of Technical Processes, Barcelona, Spain, June 30 – July 3.

Lennart Ljung participated in the 15th IFAC Symposium on System Identification, Saint-Malo, France, July 6–8. He then was a member of the Linköping University delegation to visit Nanyang Technological University in Singapore September 7–11. He also participated in the ERNSI workshop held at Stift Vorau in Austria September 30 – October 2 and in the 48th IEEE Conference on Decision and Control in Shanghai, China, December 16–18.

Christian Lundquist participated in the 4th Summer School in Simultaneous Localisation and Mapping (SLAM) hosted by the Australian Centre for Field Robotics, University of Sydney, Australia, January 20–23. He also participated in the SAE World Congress, Detroit, USA, on April 20–23, the IEEE Intelligent Vehicles Symposium, Xi'an, China, June 3–5, and the 15th IFAC Symposium on System Identification, Saint-Malo, France, July 6–8.

Johan Löfberg participated in the 20th International Symposium of Mathematical Programming, August 23–28. He also participated in the 6th IFAC Symposium on Robust Control Design, Haifa, Israel, June 16–18.

Stig Moberg participated in the Multibody Dynamics Conference in Warsaw, Poland, June 29 – October 2.

Mikael Norrlöf participated in the Korea – Sweden Robotics Workshop, Lund, Sweden, June 8–9. He also participated in the Symposium on Learning Control at IEEE Conference on Decision and Control in Shanghai, China, December 14—15 and the 48th IEEE Conference on Decision and Control in Shanghai, China, December 16–18.

Henrik Ohlsson participated in the 15th IFAC Symposium on System Identification, Saint-Malo, France, July 6–8. He also participated in the Machine Learning Summer School held in Cambridge, UK, August 29 – September 9. Henrik visited the Computational and Biological Learning Lab at the Department of Engineering, University of Cambridge, UK, August 29 – December 14. He also participated in the ERNSI workshop held at Stift Vorau in Austria September 30 – October 2 and in the 48th IEEE Conference on Decision and Control in Shanghai, China, December 16 – 18.

Umut Orguner participated in the 12th International Conference on Information Fusion, Seattle, Washington, July 6–9. He also participated in the Machine Learning Summer School held in Cambridge, UK, August 29 – September 9.

Daniel Petersson participated in the European Control Conference 2009, Budapest, Hungary, August 23–26.

Thomas Schön visited Saab AB, Linköping, Sweden, January 20. During February 17 – March 16 he visited the School of Electrical Engineering and Computer Science at the University of Newcastle, Newcastle, Australia. He also visited the Australian Centre for Field Robotics (ACFR) at the University of Sydney, Sydney, Australia, February 23. He participated in the IEEE Intelligent Vehicles Symposium, Xi'an, China, June 3–5. On June 9 he visited the Department of Electronics Engineering at Fudan University, Shanghai, China. He also participated in the 15th IFAC Symposium on System Identification, Saint-Malo, France, July 6–8. He visited the Centre for Autonomous Systems, Royal Institute of Technology, Stockholm, Sweden, August 13. He also participated in the Machine Learning Summer School held in Cambridge, UK, August 29 – September 9.

Zoran Sjanic participated in the 15th IFAC Symposium on System Identification, Saint-Malo, France, July 6–8.

Per Skoglar participated in the IEEE Aerospace Conference, Big Sky, USA, March 7–14, in the 12th International Conference on Information Fusion, Seattle, USA, July 6–9, and in the Swedish Workshop on Autonomous Robots (SWAR), Västerås, Sweden, September 8.

Martin Skoglund participated in the 4th Summer School in Simultaneous Localisation and Mapping (SLAM) hosted by the Australian Centre for Field Robotics, University of Sydney, Australia, on January 20–23.

Henrik Tidefelt participated in the 15th International Conference on Applications of Computer Algebra, Montréal, Québec, Canada, on June 25–28. He also participated in the 15th IFAC Symposium on System Identification, Saint-Malo, France, July 6–8. He also participated in the European Control Conference 2009, Budapest, Hungary, August 23–26.

Johanna Wallén participated in the European Control Conference 2009, Budapest, Hungary, August 23–26. She also attended the Symposium on Learning Control at IEEE Conference on Decision and Control in Shanghai, China, December 14–15 and the 48th IEEE Conference on Decision and Control in Shanghai, China, December 16–18.

Appendix E

Lectures by the Staff

- Daniel Ankelhed: *On Low Order Controller Synthesis Using Rational Constraints*, Techn. Lic. presentation at Linköping University, Sweden, March 27.
- Daniel Ankelhed: *A Primal-Dual Method for Low Order H-infinity Controller Synthesis*, 48th IEEE Conference on Decision and Control, Shanghai, China, December 18.
- Martin Enqvist: *Nonlinearity Detection and Impulse Response Estimation Using a Weighting Approach*, 15th IFAC Symposium on System Identification, Saint-Malo, France, July 6.
- Rikard Falkeborn: *A Decomposition Algorithm for KYP-SDPs*, European Control Conference 2009, Budapest, Hungary, August 25.
- Karl Granström: *Learning to Detect Loop Closure from Range Data*, 2009 International Conference on Robotics and Automation, Kobe, Japan, May 14.
- Fredrik Gustafsson: *Navigation and Collision Avoidance for Aircraft and Cars*, Cambridge University, UK, January 8.
- Fredrik Gustafsson: *Fusion in Sensor Networks*, Delft University, The Netherlands, November 8.
- Fredrik Gustafsson: *Collision Avoidance on Roads*, NTU-LiU workshop, Linköping, Sweden, November 17.

- Anders Hansson: *A Tailored Inexact Interior-point Method for Systems Analysis*, 3rd Nordic Optimization Symposium, Stockholm, Sweden, March 14.

- Anders Hansson: *Optimeringsbaserad klarering av styrlagar för flygplan*, Hagander Symposium, Lund, Sweden, December 10.

- Roger Larsson: *Direct Prediction-Error Identification of Unstable Nonlinear Systems Applied to Flight Test Data*, 15th IFAC Symposium on System Identification, Saint-Malo, France, July 6.

- Roger Larsson: *Real-Time Aerodynamic Model Parameter Identification*, 40th Annual International Society of Flight Test Engineering Symposium, Linköping, Sweden, September 9.

- Fredrik Lindsten: *Conflict Detection Metrics for Aircraft Sense and Avoid Systems*, 7th IFAC Symposium on Fault Detection, Supervision and Safety of Technical Processes, Barcelona, Spain, July 1.

- Lennart Ljung: *Experiments with Identification of Continuous Time Models*, 15th IFAC Symposium on System Identification, Saint-Malo, France, July 7.

- Lennart Ljung: *Developments in the MathWorks System Identification Toolbox — GUI and SIMULINK Featuers* 15th IFAC Symposium on System Identification, Saint-Malo, France, July 6.

- Lennart Ljung: *System Identification: From Data to Model — with (some) Applications to Aircraft Modeling*, 20 years of DST Control, Linköping, Sweden, August 27.

- Lennart Ljung: *System Engineering and Computer Science in Linköping*, The Nanyang Technological University, Singapore, September 9.

- Lennart Ljung: *Developments in System Identification*, The Nanyang Technological University, Singapore, September 9.

- Lennart Ljung: *Order and Structural Dependence Selection of LPV-ARX Models using a Nonnegative Garrote Approach*, (For R. Toth, C. Lyzell, M. Enqvist, P.S.C. Heuberger and P.M.J. Van der Hof.), 48th IEEE Conference on Decision and Control, Shanghai, China, December 18.

- Christian Lundquist: *Fusion av sensordata för trafiksäkerhet*, Transportforum, Linköping, Sweden, January 9.

- Christian Lundquist: *Estimation of the Free Space in Front of a Moving Vehicle*, SAE World Congress, Detroit, USA, April 23.

- Christian Lundquist: *Automotive Sensor Fusion*, Fudan University, Shanghai, China, June 9.

- Christian Lundquist: *Recursive Identification of Cornering Stiffness Parameters for an Enhanced Single Track Model*, 15th IFAC Symposium on System Identification, Saint-Malo, France, July 8.

- Christian Lundquist: *Road Geometry Estimation*, Workshop on Results of the Sensor Data Fusion System Development, Göteborg, November 11.

- Christian Lundquist: *Automotive Sensor Fusion for Situation Awareness*, Techn. Lic. presentation at Linköping University, Sweden, November 20.

- Christian Lyzell: *Handling Certain Structure Information in Subspace Identification*, 15th IFAC Symposium on System Identification, Saint-Malo, France, July 6.

- Christian Lyzell: *Identification Aspects of Ritt's Algorithm for Discrete-Time Systems*, 15th IFAC Symposium on System Identification, Saint-Malo, France, July 6.

- Christian Lyzell: *Order and Structural Dependence Selection of LPV-ARX Models Using a Nonnegative Garrote Approach*, 18th ERNSI Workshop in System Identification, Stift Vorau, Austria, October 2.

- Christian Lyzell: *Initialization Methods for System Identification*, Techn. Lic. presentation at Linköping University, Sweden, December 8.

- Johan Löfberg: *Robust Optimization and Uncertainty Modeling in YALMIP*, Institute for Systems Theory and Automatic Control, Universität Stuttgart, Germany, June 23.

- Johan Löfberg: *Robust Optimization and Uncertainty Modeling in YALMIP*, 20th International Symposium of Mathematical Programming, Chicago, Illinois, August 23.

- Stig Moberg: *Inverse Dynamics of Flexible Manipulators*, Multibody Dynamics 2009, Warsaw, Poland, July 1.

- Stig Moberg: *How to Survive when you are Weak and Blind — The Confessions of an Industrial Robot*, LINK-SIC Workshop, Linköping, Sweden, November 9.

- Mikael Norrlöf: *Industrial Robotics — Current Products and Trends*, Korea - Sweden Robotics Workshop, Lund, Sweden, June 8.

- Mikael Norrlöf: *Estimating the Tool Position for and Industrial Robot using Additional Sensors*, Korea - Sweden Robotics Workshop, Lund, Sweden, June 8.

- Mikael Norrlöf: *Some Future Research Issues in ILC — seen from an Industrial Robotics Perspective*, Symposium on Learning Control at IEEE CDC 2009, Shanghai, China, December 15.

- Mikael Norrlöf: *Estimating the Tool Position for and Industrial Robot using Accelerometer Measurements*, 48th IEEE Conference on Decision and Control, Shanghai, China, December 18.

- Henrik Ohlsson: *On Manifolds, Climate Reconstruction and Bivalve Shells*, 48th IEEE Conference on Decision and Control, Shanghai, China, December 18.

- Henrik Ohlsson: *Gray-Box Identification for High-Dimensional Manifold Constrained Regression*, 15th IFAC Symposium on System Identification, Saint-Malo, France, July 7.

- Henrik Ohlsson: *Segmentation of ARX Models*, 18th ERNSI Workshop in System Identification, Stift Vorau, Austria, October 2.

- Henrik Ohlsson: *A Review of Filtering and Smoothing*, Cambridge University, UK, November 19.

- Umut Orguner: *Distributed Target Tracking with Propagation Delayed Measurements*, 12th International Conference on Information Fusion, Seattle, Washington, July 8.

- Daniel Petersson: *Optimization Based LPV-approximation of Multi-model Systems*, European Control Conference 2009, Budapest, Hungary, August 25.

- Thomas Schön: *Sensor Fusion Supporting Autonomous Systems*, Linköping University, Linköping, Sweden, December 8.

- Thomas Schön: *The Use of Camera Information in Formulating and Solving Sensor Fusion Problems*, Linköping University, Linköping, Sweden, November 29.

- Thomas Schön: *Sensor Fusion — an Overview of Theory and Applications*, Centre for Autonomous Systems, Royal Institute of Technology, Stockholm, Sweden, August 13.

- Thomas Schön: *The Particle Filter and its Applications*, Department of Electronics Engineering, Fudan University, Shanghai, China, June 9.

- Thomas Schön: *The Particle Filter — An Engineering Perspective*, The School of Electrical Engineering and Computer Science, University of Newcastle, Newcastle, Australia, March 13.

- Thomas Schön: *Sensor Fusion — Theory, Applications and a Calibration Problem*, The School of Electrical Engineering and Computer Science, University of Newcastle, Newcastle, Australia, March 11.

- Thomas Schön: *Sensor Fusion — Theory, Applications and a Calibration Problem*, Australian Centre for Field Robotics (ACFR), University of Sydney, Sydney, Australia, February 23.

- Thomas Schön: *Nonlinear State Estimation — Introducing the Particle Filter*, Saab AB, Linköping, Sweden, January 20.

- Per Skoglar: *On Information Measures based on Particle Mixture for Optimal Bearings-only Tracking*, IEEE Aerospace Conference, Big Sky, USA, March 9.

- Per Skoglar: *Improved Target Tracking with Road Network Information*, IEEE Aerospace Conference, Big Sky, USA, March 12.
- Per Skoglar et al.: *The ARCUS Project*, SAAB, Linköping, Sweden, March 18.
- Per Skoglar: *Road Target Tracking with an Approximative Rao-Blackwellized Particle Filter*, 12th International Conference on Information Fusion, Seattle, USA, July 7.
- Per Skoglar: *Shooter Localization in Wireless Sensor Networks*, 12th International Conference on Information Fusion, Seattle, USA, July 7.
- Per Skoglar: *Planning Methods for Aerial Exploration and Target Tracking*, Swedish Workshop on Autonomous Robots (SWAR), Västerås, Sweden, September 8.
- Per Skoglar: *Planning Methods for Aerial Exploration and Ground Target Tracking*, Techn. Lic. presentation at Linköping University, Sweden, October 30.
- Per Skoglar: *Planning Methods for Aerial Exploration and Ground Target Tracking*, Seminar at Swedish Defence Research Agency (FOI), Linköping, Sweden, December 18.
- Henrik Tidefelt: *Unstructured Matrix-valued Singular Perturbations — Tackle or Avoid?*, Applications of Computer Algebra 2009, Montréal, Québec, Canada, June 25.
- Henrik Tidefelt: *Robust Point-mass Filters on Manifolds*, 15th IFAC Symposium on System Identification, Saint-Malo, France, July 6.
- Henrik Tidefelt: *On the Well-posedness of Mumerical* DAE, European Control Conference 2009, Budapest, Hungary, August 24.
- David Törnqvist: *Nonlinear Estimation Methods and Using Camera as a Sensor*, ABB, Västerås, Sweden, March 9.
- David Törnqvist: *Particle Filter SLAM*, FOI, Linköping, Sweden, June 18.

- Johanna Wallén: *Performance of ILC Applied to a Flexible Mechanical System*, European Control Conference 2009, Budapest, Hungary, August 24.

- Johanna Wallén: *A Framework for Analysis of Observer-based ILC*, Symposium on Learning Control at 48th IEEE Conference on Decision and Control in Shanghai, China, December 14.

- Johanna Wallén: *ILC Applied to a Flexible Two-link Robot Model using Sensor-fusion-based Estimates*, 48th IEEE Conference on Decision and Control, Shanghai, China, December 16.

Appendix F

Publications

Phd Theses

[1] P.-J. Nordlund. *Efficient Estimation and Detection Methods for Airborne Applications*. Linköping studies in science and technology. Dissertations. No. 1231, Jan. 2009. URL http://www.control.isy.liu.se/publications/doc?id=2104.

[2] H. Tidefelt. *Differential-algebraic equations and matrix-valued singular perturbation*. Linköping studies in science and technology. Dissertations. No. 1292, Nov. 2009. URL http://www.control.isy.liu.se/publications/doc?id=2234.

Licentiate Theses

[3] D. Ankelhed. *On low order controller synthesis using rational constraints*. Licentiate thesis no. 1398, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Mar. 2009. URL http://www.control.isy.liu.se/publications/doc?id=2123.

[4] C. Lundquist. *Automotive Sensor Fusion for Situation Awareness*. Licentiate thesis no. 1422, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Oct. 2009. URL http://www.control.isy.liu.se/publications/doc?id=2228.

[5] C. Lyzell. *Initialization Methods for System Identification*. Licentiate thesis no. 1426, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Nov. 2009. URL http://www.control.isy.liu.se/publications/doc?id=2232.

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Journal Papers and Book Chapters

[7] S. Björklund and L. Ljung. An improved phase method for time-delay estimation. *Automatica*, 45(10):2467–2470, Oct. 2009. URL http://www.control.isy.liu.se/publications/doc?id=2203.

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[14] A. Helmersson. LTV model reduction with upper error bounds. *Transactions of Automatic Control*, 54(7):1450–1462, July 2009. URL http://www.control.isy.liu.se/publications/doc?id=2211.

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Conference Papers

[24] M. Ahrholdt, F. Bengtsson, L. Danielsson, and C. Lundquist. SEFS — Results on sensor data fusion system development. In *Proceedings of the 16th World Congress of ITS*, Stockholm, Sweden, Sept. 2009. URL http://www.control.isy.liu.se/publications/doc?id=2267.

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Technical Processes, Barcelona, Spain, July 2009. URL http://www.control.isy.liu.se/publications/doc?id=2206.

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Appendix G

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Appendix H

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